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Developments on DC/DC converters for the LHC experiment upgrades

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ABSTRACT: Prototypes of DC/DC power and Point of Load (PoL) converters were designed and built with the aim of satisfying the foreseen working parameters of the High Luminosity (HL) LHC experiments, using both Silicon (Si) MOSFETs and/or more recent devices substantiated of better power performance, like Silicon Carbide (SiC) and Gallium Nitride (GaN) transistors. Optimization of their design, based on the comparison between the simulated and measured thermal, electrical and mechanical performance, is in progress, and many improvements with respect to the previous versions are under implementation. We discuss in this paper the results of the last modifications.

In addition, many tens of discrete component samples, chosen among the devices commercially available in the three different technologies (Si, SiC and GaN), were electrically characterized and tested under $\gamma$-rays, neutron, proton and heavy ion radiation, also using a combined run method.

We have also planned to test some commercial DC/DCs under the extreme conditions of radiation and magnetic field expected in the upgrades of the LHC experiments. Here we show the first results on few samples.

KEYWORDS: Radiation-hard electronics; Voltage distributions
1 Introduction

The increase of the radiation background [1–4] and the requirements of new front-end electronics that will characterize the HL-LHC upgrades [5–8] are not compatible with the current capability of the power supply systems in use. They will have to face a highly hostile environment, basically from the background of both charged and neutral particles, of the order of five times higher than the LHC nominal one. They must operate also in presence of a non negligible magnetic field, whose peak value strongly depends on their physical position, and can range from 100 mT on the balconies up to 2 T close to the detectors. These requirements open a severe tolerance issue for component selection and system design.

Moreover, the necessity of reducing the power loss in cables, in order to increase the overall efficiency of the system in view of a more demanding power consumption of the detectors, requires to place the PoLs as close as possible to them, in a much more worse environment compared to the one of the racks in balconies.

A possible solution involves the development of a distributed power supply network, where PoLs, deployed at the very heart of the detectors, are supplied by power units, delivering high current at a fixed voltage in the range 12 V to 24 V (or 48 V) and placed inside racks, far from detectors. In this way, only the PoLs will work in a very harsh environment.

The system described in the present article is an improvement of the one previously developed [9], and is based on a power converter, called Main Converter (MC), able to cope with the electrical requirements of the ATLAS LAr calorimeter, and a high-current PoL \( I_{\text{out}} = 10 \, \text{A} \) designed with the last generation of GaN transistors.
Figure 1. The proposed MC. Numbers labeling the thermocouples used for experimental characterization of the MC will be discussed in the following.

Table 1. Specifications of the MC.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage $V_i$</td>
<td>280 V</td>
</tr>
<tr>
<td>Output Voltage $V_o$</td>
<td>12 V</td>
</tr>
<tr>
<td>Nominal output power</td>
<td>up to 1.0 kW</td>
</tr>
<tr>
<td>Max output power</td>
<td>up to 1.5 kW</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>100 kHz</td>
</tr>
</tbody>
</table>

Radiation tests of discrete components are still in progress, and here we present the last results on two device technologies, SiC and GaN. We have also tested one commercial DC/DC converter under $\gamma$-rays and in B-field, and the results are shown here.

2 The power converter

The design of the MC is based on a modular approach, in order to improve the overall reliability of the system and provide the requested redundancy [10]. The transient-resonant topology adopted is based on a Switch-In-Line-Converter (SILC) [9, 11].

The proposed topology features multiple outputs, low switch voltage stress, soft switching operation, first order dynamic, limited overall power losses and, finally, generated Electro-Magnetic Interference (EMI) in compliance with the LHC requirements. A picture of the implemented and tested MC is reported in figure 1. In table 1 the main features of the MC have been detailed. Further details about the MC can be found in literature [9, 11–16].

Galvanic isolation is obtained using a planar transformer, in order to reduce dimensions and, consequently, iron losses. The selected transformer core material is Kool Mu 60 $\mu$m, which allows
for the following performance: \(i\) low losses at high temperatures, \(ii\) high saturation (1.05 T), \(iii\) lower core loss than powdered iron, \(iv\) moderate cost, \(v\) low magnetostriction, \(vi\) very high Curie temperature, \(vii\) stable performance with temperature, \(viii\) variety of available shapes.

Transformer windings are obtained using four 22-layer PCBs. Details on the fabrication and electrical connections were described in [14]. In the last revision of the MC, the PCBs of the planar transformer have been replaced by copper windings separated by Kapton sheets.

2.1 Improvements to the previous design

More recent researches and experimental activity were devoted to obtain better performance from the implemented specimen. In particular, we adopted a specifically designed cold plate, as described in the following. Connection to the external power cables have been improved, due to the fact that in previous tests we observed overheating in this area. Further, auxiliary power supply and controller circuits have been replaced by more efficient solutions. The obtained efficiency during the tests was higher than 80% at the maximum delivered power, 1.5 kW.

2.2 Design of the cold plate

The adopted cold plate is depicted in figure 2. The experimental results reported in this paper are obtained with the following set points: \(P_{\text{out}} = 1.2 \, \text{kW}, \ P_{\text{d}} = 240 \, \text{W}, \ T_{\text{inlet}} = 18^\circ \text{C}, \max \ T_{\text{outlet}} = 25^\circ \text{C}, \ T_{\text{amb}} = 28^\circ \text{C}, \ \text{water flow rate} = 0.63 \text{ l/m}. \) Figure 3 shows the simulation results of water flow and
temperatures at the boundaries (see also [15] and [16]). The adoption of this kind of cold plate allows the MC to operate at the maximum delivered power of 1.5 kW with reasonable temperatures. Note that, in order to obtain this result, the thermal coupling between the transformer and the cold plate has been improved.

2.3 Measurements

Predictions obtained by simulations were tested experimentally. The installed setup is shown in figure 4. Temperatures are monitored by a FLIR A325 infrared thermo-camera. Differential inlet/outlet water temperature is monitored by means of a thermometer based on $k$-type thermocouples at the input and at the output of the cold plate. The minimum measured differential temperature was 1.7°C and the maximum was 2.7°C. Mean value was about 2.2°C. Finally, inner temperatures are also monitored by thermocouples (see table 2 and figure 1). The MC works properly at the maximum planned delivered power (1.5 kW). High values of temperature that could compromise the reliability of the system have not been registered.
3 The GaN transistor PoL

In the above-mentioned distributed power supply scenario, PoL converters are used to scale down the distributed bus voltage to the value needed by the detector electronic loads. Because of their location, very close to the loads, they are requested to operate in a very harsh environment. To this purpose, the use of commercially available normally off GaN power MOSFETs (EPC2015 40 V–33 A) has been investigated in a synchronous buck converter, switching at 1 MHz, whose scheme is shown in figure 5. We have used a dedicated driver, the LM5113 available from Texas Instruments, which allows for turn-on and turn-off operations under controlled conditions. The LTC3833 by Linear Technology, implementing an inner valley current control loop driven by an external output voltage control loop, is used as a standard synchronous buck controller. The control loop regulates the output voltage at $V_o = 1.2$ V, while the maximum load current is essentially limited by the thermal characteristics of the board.

We built two prototypes, whose layout is shown in figure 6, where the main power and control components are highlighted. A simple 2-layer PCB was used, limiting the load current to 10 A.

Main converter waveforms in a switching period are reported in figure 7: the fast switching characteristic of the GaN devices is likely to induce ringing in the switching node, as revealed by the zoomed waveforms in figure 7(b).
Figure 7. Measured waveforms in a switching period with $V_g = 12$ V, $I_o = 10$ A [(a): 200 ns/div, (b): 20 ns/div]. From top to bottom: output voltage $v_o$ [200 mV/div], output current $i_o$ [2 A/div], switching node voltage $v_{sw}$ [5 V/div].

Figure 8. Efficiency comparison between two different prototypes.

The measured efficiency of the two prototypes at different load current values is shown in figure 8. The non negligible difference between the two apparently identical prototypes is mainly caused by differences in the switching dead times, which are manually adjusted to minimize the GaN internal diode conduction interval. Such dead times are clearly visible in the negative portion of the switching node voltage of figure 7(b) close to the commutation instants.

4 Radiation tests on SiC and GaN devices

We tested power MOSFETs manufactured by CREE on SiC rated at 1200 V–24 A, and two types of enhancement-mode GaN High Electron Mobility Transistors (HEMTs) from Efficient Power Conversion (EPC), having a blocking voltage of 40 or 200 V, a maximum continuous $I_{ds}$ current of 12 or 33 A and a maximum pulsed current of 60 or 150 A [17].
The devices were exposed to several sources of radiation at the following facilities: $\gamma$-rays at CALLIOPE, ENEA-UTTMAT in Casaccia, Rome, Italy; neutrons at TAPIRO, ENEA in Casaccia, Rome, Italy; low energy protons at CN accelerator of Laboratori Nazionali di Legnaro (LNL), INFN, Padua, Italy; heavy ions at TANDEM-XTU and TANDEM-ALPI accelerators of the Laboratori Nazionali di Legnaro (LNL), INFN, Padua, Italy.

### 4.1 Results

To evaluate the effect of $\gamma$-rays both on SiC and GaN MOSFETs, 25 samples for each type and 5 samples for each dose were irradiated. All devices were characterized before the irradiation, then they were irradiated with doses ranging from 573 Gy up to 10.8 kGy, and finally they were submitted to a thermal annealing process.

The devices characteristics were again measured and the dependence of the quantities of interest in relation to the dose absorbed were obtained.

The main effects of $\gamma$-ray irradiations on the characteristics of SiC MOSFETs were observed on the threshold voltage, whose value is reported in figure 9 as a function of the absorbed dose. A significant reduction of the threshold voltage was measured at increasing doses down to $-0.25$ V at 10.8 kGy. Small changes were observed in $R_{on}$ and $I_{GSS}$ up to the highest dose, as shown in figure 10 and figure 11, respectively.

During our tests, SiC power MOSFETs did not exhibit Single Event Effects (SEE) induced by neutrons. In fact, no Single Event Burnout (SEB) or Single Event Gate Rupture (SEGR), were detected up to $2.7 \times 10^{12}$ n/cm$^2$ 1 MeV equivalent (Si). On the contrary, these devices showed a significant sensitivity to SEE induced by heavy ions. The voltage at which the devices can be safely used drastically reduces down to 100 V, as shown in figure 12, in presence of highly energetic heavy ions. This limitation does not affect the use of SiC power MOSFETs in the LHC upgrades, for which this probability is very low.

The same procedure described above was used to investigate the behavior of GaN HEMT devices having a blocking voltage of 40 V and 200 V after exposure to $\gamma$-rays. Variations in threshold voltage, $R_{on}$, $I_{GSS}$, and breakdown voltage after $\gamma$-rays are negligible up to the maximum dose of 10.8 kGy. The same devices were also irradiated with 3 MeV protons up to a fluence...
of $4 \cdot 10^{14}$ p/cm$^2$. The exposure induced an increase in gate current up to one order of magnitude, a threshold voltage reduction up to 1 V, and a transconductance drop up to 30%, as shown in figure 13.

Both 40 V and 200 V blocking voltage GaN HEMTs were irradiated with heavy ions. Neither SEB nor SEGR were detected up to the maximum rated voltage on both the drain and gate terminals. GaN HEMTs have shown also a very good tolerance to total dose radiation effects.

5 Tests on commercial DC/DCs

An integrated DC-DC step-down converter by Linear Technologies (LTM4619) [18] has been tested for magnetic field (B-field) and TID (Total Ionizing Dose) tolerance. For test purposes we used evaluation boards provided by the manufacturer, with one module mounted per board. Each module has two channels, each one with a specified efficiency of $\sim 80\%$.

A test for magnetic field tolerance has been performed in INFN-LASA Laboratory in Milan: one demo board was placed between the polar expansions of a dipole magnet, with B-field aligned along the major axes of the converter once at a time.
Figure 12. Failure voltage during the 79Br irradiations as a function of the beam energy.

Figure 13. Transconductance and drain current of an enhancement-mode GaN HEMT before and after irradiation with \(3 \cdot 10^{14}\) 4-MeV p/cm\(^2\).

Input voltage was 20 V, both outputs were 1.8 V–3 A. We measured the conversion efficiency \(\eta = P_{\text{OUT}} / P_{\text{IN}}\) of the device along the three orientations (X, Y and Z), whose plot is shown in figure 14 together with the test setup. No permanent effect was observed when the B-field was removed.

Two LTM4619 demo-boards were tested for TID effects at ENEA Calliope \(\gamma\) Irradiation Facility, up to 2.1 kGy TID and a dose rate of 22 Gy/h. During the test one output was at 1.8 V and the other at 3.3 V, the current for both channels was 3.4 A, the input was 24 V, the efficiency at test beginning was \(\eta = 68\%\), lower than expected and probably due to the demanding load.

During the irradiation we monitored the input current to evaluate the change in efficiency. It increased of some 10\% for a few times, then returning to initial value. After 1.7 kGy irradiation, the current dropped continuously until a complete failure of the modules after 2.1 kGy on average. The measurements are shown in figure 15.
Figure 14. The B field test setup (a), and the LTM4619 measured efficiency along the three orientations (b).

Figure 15. LTM4619 input current with respect to the TID integrated dose for both channels.

Since the output voltages were not monitored, we infer that the current increase was due to an efficiency decrease, while the current drop was the effect of an output voltage decrease due to impaired regulation capabilities.

In the near future we will perform TID tests with different dose rates on similar devices, with a monitoring system capable of recording online the output voltages. We also plan to test other commercial DC-DC converters under TID and B-field.

6 Conclusions

The first version of the MC was improved and the thermal performance at full power was satisfactory. Next steps will concern the reliability and industrialization of the design.
Two PoLs designed with GaN transistors were realized and bench tested, showing very good performance. We will test them under radiation and in B field in the near future.

Several tens of discrete devices, SiC and GaN transistors, were irradiated in various facilities. SiC devices showed a good robustness with neutrons and protons and a weakness under energetic heavy ions, while GaN devices are essentially unaffected by any type of radiation up to the target values.

Finally, we started irradiation and B-field campaigns on commercial DC/DC converters, aiming to find market existing good devices at very low cost, compared to the custom solution. The first tested device didn’t meet our requirements, but we are confident to be able to improve this performance in the next couple of years, either refining the test parameters or seeking for new designed devices.

Acknowledgments

The cold plate was realized in the mechanical workshop of the INFN Pavia by A. Freddi, C. Scagliotti and F. Vercellati, with the usual precision and prompt availability.

References


